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Study of Optical Point Sensors, Quasi-Distributed, and Distributed Optical Fiber Sensors and their Applications

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ABSTRACT
Optical sensors have emerged as vital tools in modern sensing technology owing to their sensitivity, immunity to electromagnetic interference, lightweight structure, and capability to operate under harsh environmental condition, By employing optical fiber as both transmission and sensing media, they enable accurate measurement of parameter such as temperature, strain, vibration. And pressure. Particularly Fiber Bragg Grating (FBG) in uniform. Chirped, log-periodic, and tilted forms, offer localized high-precision measurements and are widely applied in structural health monitoring, biomedical devices, and aerospace systems. Quasi-distributed sensors enhance coverage by multiplexing multiple FBGs through time-division or wavelength- division schemes, enabling efficient long-distance monitoring. Distributed sensors, utilizing Rayleigh, Raman, and Brillouin scattering, provide continuous real time sensing along the full fiber length, proving indispensable in large-scale application such as geotechnics, pipelines, energy infrastructure, and transportation systems. Advances in fabrication techniques, multiplexing methods, and signal processing algorithms have significantly improved resolution, accuracy, and multi-parameter sensing capabilities. Key challenges remain in addressing temperature –strain cross sensitivity, long*range accuracy, and interrogation complexity. Future directions emphasize sensor miniaturization, hybrid designs, and integration with smart monitoring systems to meet the increasing demand for intelligent, scalable themselves as transformative technologies across multidisciplinary fields, robust and versatile platforms for next-generation monitoring and diagnostic applications.

Keywords
Optical fiber sensor, FBG, Quasi-distributed sensing, DOFS, Rayleigh scattering, Raman scattering, Brillouin scattering.

1 INTRODUCTION
Optical fiber sensors have emerged as a vital class of sensing technologies in modern scientific and industrial applications due to their unique advantages, including high sensitivity, immunity to electromagnetic interference, lightweight structure, and the ability to operate in harsh environments. These sensors utilize optical fibers as the medium for both transmitting and sensing light, enabling the detection of a wide range of physical, chemical, and biological parameters such as temperature, strain, pressure, vibration, pH, and chemical concentrations. Optical fiber sensors are broadly classified into point sensors, quasi-distributed sensors, and distributed sensors. Optical point sensors utilize a discrete sensing element at a single location along the fiber, typically based on phenomena such as Fiber Bragg Gratings (FBGs), Log-periodic Fiber Grating (LPG), Chirped Fiber Grating and Tilted Fiber Grating (TFG). These sensors provide localized, high-precision measurements of physical or chemical parameters. To extend sensing capabilities over a broader area without sacrificing localization, quasi-distributed optical fiber sensors employ multiple discrete sensing elements (often FBGs) inscribed along a single fiber. Each sensor reflects a specific Bragg wavelength, enabling spatial multiplexing and multi-point monitoring along the fiber. In contrast, distributed optical fiber sensors provide continuous monitoring over the entire length of the fiber, with sensing capabilities derived from intrinsic scattering mechanisms such as Rayleigh, Raman, or Brillouin scattering. These systems enable truly distributed measurement of temperature, strain, or vibration with meter- to centimeter-scale spatial resolution over tens of kilometers. Distributed sensors are especially valuable in long-range and inaccessible environments such as pipelines, railways, and large-scale geotechnical monitoring.

2 CLASSIFICATION OF OPTICAL FIBER SENSOR
Based on sensing mechanisms, optical fiber sensors can be classified as shown in Fig 1.

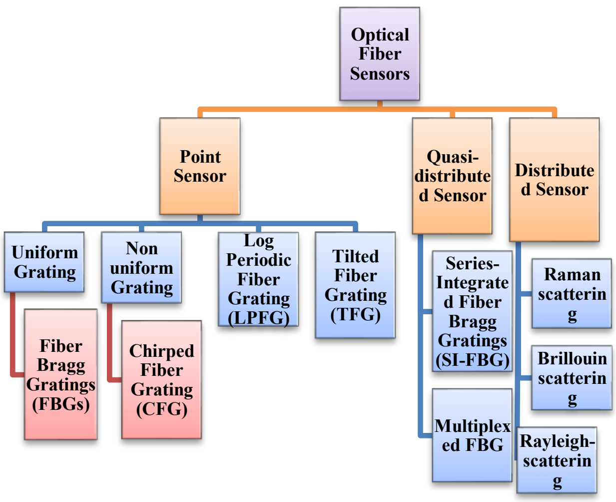

Fig 1: Classification of optical fiber sensor

2.1 Uniform Fiber Bragg Gratings (FBGs)
Uniform Fiber Bragg Gratings (FBGs) are a type of optical fiber sensor or filter in which the refractive index of the fiber core is periodically modulated along a certain length with a constant grating period (Λ). Uniform FBGs act as wavelength-selective mirrors whose reflection properties are determined by

the uniform periodic modulation of the refractive index within the fiber core

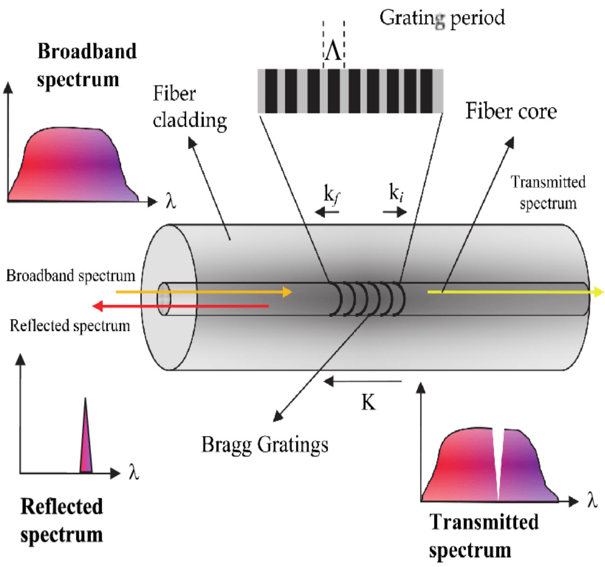

Fig 2: Uniform fiber grating structure with typical input, transmitted and reflected spectrum[1]

2.2 Chirped fiber grating

Chirped fiber Bragg grating has varying periodicity along the grating's length. These FBGs are fabricated using a UV beam and a phase mask to create the desired index modulation. [2]. Chirped fiber grating offer better scattering compensator to improve Q-factor and minimization of bit error rate (BER) [3].

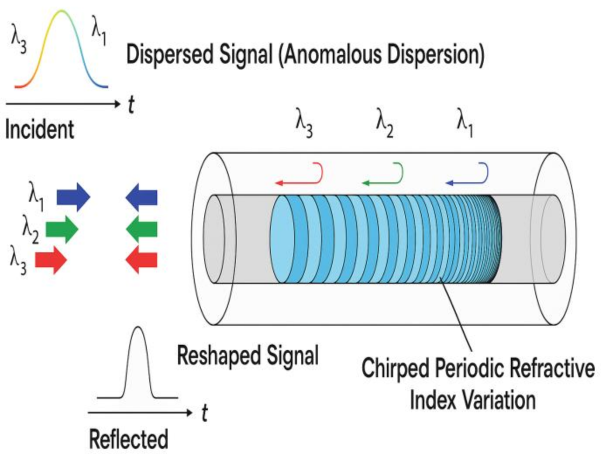

Fig 3: Chirped fiber grating structure with incident and reflected wave [2].

2.3 Log-periodic fiber grating (LPFG)

In this fiber grating structure the modulation of refractive index along the length of fiber and the period of modulation use the logarithmic scale. LPFG can be fabricated using various techniques, such as UV exposure, phase mask method or point to point inscription [4]. Applications band –rejection filters, gain- flattening filters [5].

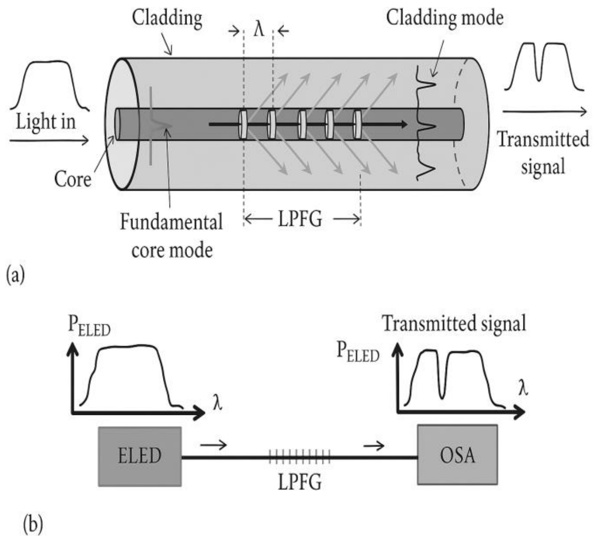

Fig 4: Log-periodic structure typical transmitted wave

2.4 Tilted fiber grating (TFG)

In this type of fiber grating a specialized type of optical fiber grating structure is used where the grating lines or periodic structure are intentionally tilted or inclined with respect to fiber axis [6].

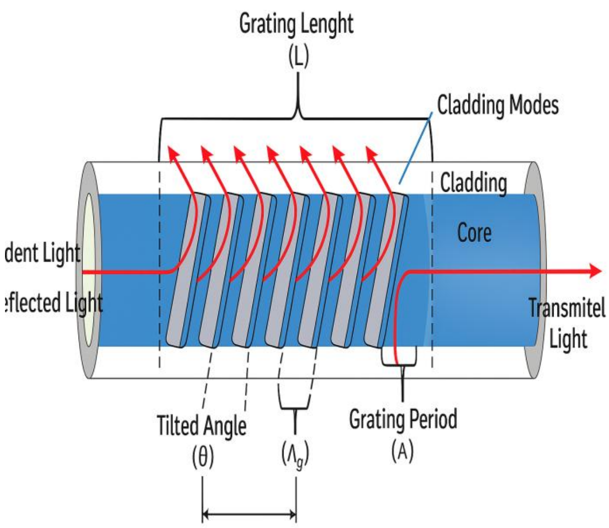

Fig 5: Tilted fiber grating (TFG) structure

3 LITERATURE REVIEW ON FBG SENSOR

Zhang, Jiarui et. al.[7]. Fiber Bragg Grating (FBG) accelerometers are highly sensitive sensors immune to magnetic interference, suitable for extreme environments. They are applied in oil exploration, seismic monitoring, and aerospace, with ongoing advancements expected to enhance their design and integration with other technologies.

Jalil, Muhammad Arif Bin et al.[8]. Fiber Bragg Gratings function by exposing a single mode fiber core to UV laser light, creating a periodic refractive index modulation. This grating reflects specific wavelengths (Bragg wavelength) while transmitting others, with shifts in reflected wavelength indicating changes in strain or temperature.

Xing, S Y. et al. [9]. Fiber Bragg Gratings operate on the principle that changes in temperature and stress alter the reflection center wavelength. This sensitivity allows for precise measurements, making them effective for structural health monitoring applications due to their high accuracy and lightweight design.

A. Kadhim, Dr. Shehab et al. [10]. In this paper a temperature sensor for the range (20-70) degree centigrade, the temperature sensor is very sensitive to variation of temperature. Here they found the sensitivity of temperature was (1-6pm\0.1°C).

K. R. Tariq, et al. [11]. In this paper FBG based sensor design and simulate for various temperature measure and single mode fiber is used, for the simulation optical simulation software is used. They compare accuracies of FBG sensing systems. Accuracy over the range of 0-320°C

C. K. Jha, et al. [12] The paper highlights that the Fiber Bragg Grating (FBG) sensor in the glove demonstrates a sensitivity of 18.45 pm/degree and an accuracy of 0.40°, indicating superior performance compared to traditional inertial measurement unit sensors in flexure sensing applications.

Jalil, Muhammad Arif Bin et al. [13] This paper is demonstrated FBG as a temperature sensor and their industrial application. Fiber Bragg Gratings (FBGs) reflect specific wavelengths of light while transmitting others, making them effective in temperature sensing. They are utilized in various applications, including industrial monitoring and chemical analysis, to detect environmental changes and prevent accidents or fires.

Brik, Fatima et al. [14] Optical Fiber Bragg Gratings (FBGs) are sensors that detect strain through changes in grating period, demonstrating high sensitivity. They are applicable in biomedical settings, capable of operating under various environmental factors like electromagnetic interference, humidity, and temperature fluctuations.

Zhang, W. et al. [15] Fiber Bragg gratings are lightweight, dielectric sensors immune to electromagnetic interference, offering chemical passivity and flexibility. Their ability to be multiplexed and perform multi-parameter sensing makes them highly competitive for various aerospace applications, enhancing structural health monitoring and safety.

Maske, Shrikant M. et al. [16] Fiber Bragg gratings (FBGs) are optimized for sensor applications, particularly in structural health monitoring. Key characteristics include high reflectivity (0.9945 a.u.), low full width at half maximum (0.848 nm), and low side lobe power (0.3393 a.u.).

Rohan, R. et al. [17] The paper reviews recent advancements and challenges in using FBG sensors for biomechanical devices, temperature monitors, respiratory monitors, and bio-sensing applications. Fiber Bragg grating sensors have become increasingly attractive for various biomedical applications.

4 QUASI-DISTRIBUTED OPTICAL FIBER SENSOR

The multiplex of sensor commonly known as quasi-distributed optical fiber sensors, represents a significant technological advancement over traditional point sensor configurations, in this scheme multiple localized sensor are placed at interval along the fiber length as shown in Fig 6 (a). Quasi-distributed optical fiber sensors represent a significant advancement in fiber optic technology, enabling the measurement of various physical parameters over extended distances with high precision [18][19][20]. These sensors utilize optical fibers as sensitive elements, allowing for continuous and distributed sensing capabilities. This technology is particularly beneficial in applications requiring long-distance monitoring, such as telecommunications, geophysics, and environmental monitoring. The point sensors or FBGs are multiplexed using wavelength division multiplexing (WDM) or time division multiplexing (TDM) [14][21].

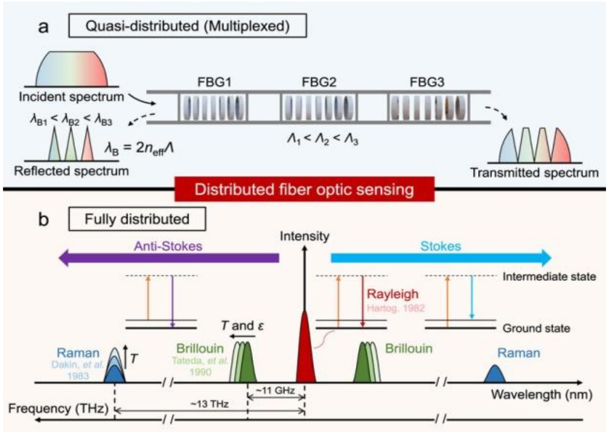

Fig 6: Distributed optical fiber sensor[21] (a) quasi-distributed sensor (b) distributed sensor

Time-division multiplexing (TDM): Each FBG is interrogated in a specific time slot, allowing for independent characterization of each grating. Wavelength-division multiplexing (WDM) Multiple FBGs with different Bragg wavelengths are interrogated simultaneously using a wavelength division multiplexer (WDM).

4.1 Literature Review on Quasi-Distributed sensor

K. Kuroda, et al. [21]. In this paper, author discussed a quasi-distributed optical fiber sensor system using time-division multiplexing to interrogate fiber Bragg gratings. It successfully detects weak reflections from gratings located at varying distances, demonstrating effective signal-to-noise ratios for long-distance sensing applications. This method enables the detection of weak reflections from FBGs located at various distances, such as 14 m, 2 km, and 42 km, with a reflectivity of 1%

T. Eftimov et al. [22] The paper discusses a quasi-distributed optical-fiber sensor utilizing an array of corrugated long-period gratings (C-LPG) to spatially locate phosphors. This sensor measures temperature through time-dependent responses, enabling contactless interrogation via a smartphone within the 0 °C to 100 °C range.

A. Sanchez-Gonzalez et al. [23] The study presents a quasi-distributed optical fiber sensor using in-line interferometers for vibration and strain monitoring, achieving 3-cm spatial resolution. It employs capillary fiber segments as strain point sensors and reflectors, enabling multi-parameter measurements through the Doppler Effect.

Zhong, Shuda et al.[24]. In this paper author developed a quasi-distributed optical fiber pressure sensor and he estimated pressure using wavelength change measurements using numerical methods. Quasi-distributed fiber sensors, utilizing fiber Bragg gratings, are applicable in various fields requiring reliable pressure measurement, such as flow regulation, volume control, and product quality assurance, particularly in harsh environments where traditional gauges are inadequate.

Ohodnicki, Paul R et al. [25]. In this paper quasi-distributed fiber optic sensing technology is applied in structural health monitoring (SHM), particularly through integration with traditional acoustic non-destructive evaluation methods, enhancing the ability to assess the integrity and performance of energy infrastructure effectively.

Deng, Yuanpeng et al. [26]. The quasi-distributed fiber-optic acoustic sensor can be applied in monitoring vibrations and dynamic strain in various environments, such as structural health monitoring, environmental sensing, and security applications, due to its low cost, simple configuration, and high sensitivity.

5 DISTRIBUTED OPTICAL FIBER SENSOR

Distributed optical fiber sensors represent a significant advancement in monitoring and measurement technology, utilizing the inherent advantages of optical fibers to detect various physical parameters such as temperature, strain, and pressure. Unlike traditional sensors, which are limited to point measurements, distributed sensors provide data along the entire length of the fiber, allowing for comprehensive environmental analysis. This capability is particularly beneficial in fields such as structural health monitoring, where real-time assessments of building integrity can prevent catastrophic failures. Furthermore, their robustness and immunity to electromagnetic interference make these sensors ideal for the deployment in challenging environments, such as industrial plants and atmospheric studies. Recent innovations have seen the integration of advanced signal processing techniques, enhancing the accuracy and efficiency of data collection, thus solidifying the role of distributed optical fiber sensors in modern technological applications. Their versatility continues to unlock novel solutions across various industries, emphasizing their growing relevance.

5.1 Classification of distributed fiber optical sensor

While us sending light or pulse inside the optical fiber there is interaction of an incident light with a medium, where the photon transfers part of its energy to the medium, exciting it to a higher vibrational or rotational state. Leaser light gets scattering in optical fibers due to change in the refractive index of the medium. Due to scattering we will get reflected wave (i.e. stock and anti-stock). The concept of scattering is used to design optical fiber sensor Based on scattering technique, distributed optical sensors are classified as Raman-based, Brillouin-based, and Rayleigh-based optical sensors.

5.1.1 Raman scattering

Raman scattering-based distributed optical fiber technology has emerged as a pivotal method for temperature sensing across various applications. This technique leverages the temperature-dependent nature of Raman scattering to provide real-time, distributed temperature measurements along the fiber length. Principles of Raman Scattering in optical fiber, scattering involves the inelastic scattering of light, where incident photons interact with molecular vibrations, resulting in a shift in wavelength. The anti-Stokes component of the scattered light is sensitive to temperature changes, making it suitable for temperature measurement as shown in Figure 4 [27]. Through a comparison of the backscattered light intensity in the Stokes band (Lower-energy or longer wavelength, components of scattered light. and anti-Stokes bands, we can determine the temperature and location more accurately. [28]

5.2 Literature Review on Raman scattering

Pieracci, et al. [29] The paper presents a novel Raman Scattering-based Distributed Temperature-Sensing system using multimode optical fibers at 800 nm, focusing on short-range applications with a temperature measurement precision of ±3 °C and a spatial resolution of 8 m.

Kumar, Kishore et al. [30] In this paper Raman scattering-based distributed optical fiber sensing utilizes Raman Optical Time Domain Reflectometry (ROTDR) to measure temperature along the fiber's length by detecting weak anti-Stokes backscattered light, enabled by a high gain bandwidth optical receiver for enhanced sensitivity.

Yang, Taolue et al. [31] In this paper Raman scattering-based distributed optical fiber temperature sensing technology measures temperature across various applications. This study evaluates its performance in cryogenic environments, revealing accurate measurements from room temperature to 65K, but significant errors at lower temperatures due to increased fiber stress and reduced scattering intensity.

Lu, Lidong et al. [32] The paper presents a novel distributed optical fiber temperature sensor utilizing Raman anti-Stokes scattering light, demonstrating temperature sensitivity, In this paper the experimental demonstration of sensor system which consists of approximately 3.5 km of optical fiber. The proposed design achieves a dynamic range of 24 dB using 20 ns pulse width, and measurements of temperature are performed between30.0 °C and 80.0 °C. The results indicate a maximum temperature deviation of +1.5°C to +1.6°C, and a root square error (RMS) of 0.3°C over the entire temperature range.

Wang, Chenyi et al. [33] In this paper Raman scattering-based distributed optical fiber sensing utilizes the Raman scattering effect to detect temperature variations along the fiber. The proposed chaos Raman scheme enhances spatial resolution to 10 cm over 1.4 km, significantly surpassing traditional methods by 50 times.

Liu, Zhuyixiao et al. [34] The paper discusses a distributed sensing method using spontaneous Raman scattering in few-mode optical fiber, enabling simultaneous measurement of temperature and curvature. It utilizes Raman anti-Stokes and Stokes lights, achieving a temperature uncertainty of 0.24 °C and spatial resolution of 1.8 m.

5.2.1 Brillouin scattering

In this method or technique, leaser light will be sent over the optical fiber if their is change in strain, its make changes in the effective refractive index and temperature variations can cause an incident light to become a scattered photon in the core of an optical fiber. At the source end, a low-power, low-frequency backscattered wave (Brillouin frequency shift) is received. Brillouin scattering-based distributed optical fiber sensing has emerged as a significant technology for various applications, particularly in monitoring and analyzing physical parameters along fiber optic lines. This technique leverages the interaction of light with acoustic waves in the fiber, enabling high-resolution measurements over extended distances.

5.3 Literature Review on Brillouin scattering

W. P. Ng et al. [35] In this paper the sensing fiber, the frequency error of the conventional BOTDR and wavelength diversity BOTDR are 0.65 MHz and 0.18 MHz, respectively. Therefore, at the far end of the sensing fiber, the accuracy of strain and temperature measurements are 3.6 με and 0.16oC, respectively (the calibrated strain and temperature coefficients of the sensing fiber are 0.05 MHz/με and 1.07 MHz/oC).

Soto, et al. [36] In this paper a unique expression for predicting the uncertainty in determining the Brillouin frequency shift in BOTDA sensors has been designed and confirmed by rigorous experimental verification using simple physical and statistical models. Using this calculation, the true accuracy of determining the Brillouin frequency shift may be accurately predicted from a single measurement of the SNR in the sensor response at the receiver.

Zhang, Mingjiang et al. [37]. The paper discusses conventional Brillouin distributed optical sensing technology, which faces challenges in achieving spatial resolution below 1 m due to pulse width limitations and a trade-off between measurement range and spatial resolution, impacting practical applications.

Lalam, Nageswara et al. [38]. The paper discusses a multi-parameter fiber sensing system utilizing stimulated Brillouin scattering in a double-Brillouin peak fiber, enhancing Brillouin gain response for accurate strain and temperature measurements, thus improving performance over traditional multi-Brillouin peak fibers.

5.3.1 Rayleigh-scattering

Rayleigh scattering-based distributed optical fiber systems have emerged as a pivotal technology in various sensing applications, leveraging the unique properties of Rayleigh backscattering to monitor physical parameters over extended distances. Rayleigh scattering is a phenomenon where photons are scattered by sub-wavelength objects, such as small particles or molecules. It is considered to be an elastic scattering process, meaning that the energy of the photons is conserved during scattering. In this type of scattering of light is random within the core of optical fiber.

5.4 Literature Review on Rayleigh-scattering

Matveenko, Valerii et al. [39]. The paper discusses distributed strain measurements using Rayleigh scattering in optical fibers, highlighting challenges posed by fiber Bragg gratings (FBGs) with 70% reflectivity. It proposes a windowed Fourier transform method to eliminate insensitive zones in these measurements.

De Borggraef, Louis Alliot et al. [40]. In this paper author discusses distributed sensors based on Rayleigh scattering for monitoring vibrations and localizing acoustic sources, achieving a spatial resolution below 1 cm and an acquisition rate of 20 kHz, enhancing the ability to detect localized and rapid phenomena.

Araki, Eiichiro et al. [41] In this paper Rayleigh scattering-based distributed optical fiber sensing (DAS) utilizes the Rayleigh scattered wave to measure strain changes along the fiber. This technology is sensitive and suitable for observing rapid phenomena, but faces challenges with slow changes overlaid by rapid events.

N. Lalam et al. [42] The paper discusses a hybrid sensor system utilizing Rayleigh scattering for monitoring acoustic vibrations through phase-sensitive optical time domain reflectometry (Φ-OTDR), alongside Brillouin scattering for strain and temperature measurements, enhancing multi-parameter sensing capabilities in distributed optical fiber systems. Monitors strain, temperature, and vibrations over 25 km fiber.

Du, Yang et al. [19] The paper presents a Rayleigh scattering-based single mode-graded index multimode-coreless fiber structure for distributed liquid detection, enabling high-precision identification and size estimation of liquid droplets, thus enhancing the capabilities of optical fiber sensors in industrial applications.

6 CONCLUSION

For monitoring and sensing physical parameters, optical fiber sensing technologies have been shown to be the most effective. For industrial applications and monitoring the structure health, real-time monitoring of this parameter is crucial. To monitor the physical parameter temperature and strain etc. optical fiber Bragg gating sensor are the most effective and accurate sensing technique.

Quasi-distributed optical fiber sensors represent a transformative leap in optical fiber sensor technology, offering high-precision, long-distance monitoring capabilities through the strategic placement of multiple localized sensors along the fiber length. This advanced configuration leverages techniques like time-division multiplexing (TDM), and Wavelength division multiplexing (WDM) to interrogate Fiber Bragg Gratings (FBGs) or other optical elements, enabling efficient data acquisition and multiplexing for various applications particularly in temperature and pressure monitoring, as well as structural health assessments. These sensors leverage the unique properties of optical fibers to provide real-time, accurate measurements across different environments.

Distributed optical fiber technology has proven to be a groundbreaking method for temperature sensing, offering real-time, high-precision, and distributed measurements along optical fiber lengths. This technique leverages the inelastic scattering of light, particularly the temperature-sensitive anti-Stokes and Stock component, to enable accurate determination of temperature, strain and spatial location.

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